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# Efficiency measurement of a Si(Li) detector below 6.0 keV using the atomic-field bremsstrahlung

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**Abstract** : The atomic-field bremsstrahlung spectrum produced in bombardment of atoms by an electron beam of keV-energies has been used to determine the relative efficiency of a Si(Li) detector in the energy range of 2.0–7.5 keV. The relative efficiency of the detector as a function of photon energy is obtained by normalising the observed bremsstrahlung spectrum to the corresponding theoretical cross sections. The relative efficiency is put on an absolute scale using a calibrated radioactive source. This technique is illustrated by measuring the bremsstrahlung spectrum produced by 7.0 keV and 7.5 keV electrons incident on (semi-thick) targets of Ag, Au and Hf. The present method is believed to be as precise as the conventional technique using calibrated radioactive sources.

**Keywords** : Atomic-field bremsstrahlung, efficiency of a Si(Li) detector

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## 1. Introduction

A precise knowledge of the efficiency of solid state detectors, for example, of a Si (Li) detector, is important in many applications. A recent paper by Campbell and Mc Ghee [1] reviews the current state-of-the-art with regard to Si(Li) detector and provides an extensive bibliography for the work on efficiency measurement. The approach adopted is normally the traditional one which uses the carefully prepared, calibrated radioactive sources with X-rays having photon energy region of interest. Efficiency calibration of Si(Li) detectors with X-ray reference sources at energies between 1.0 keV and 5.0 keV, has been discussed by Denecke *et al* [2]. This method is known to utilise the data on nuclear- and atomic-physics processes, such as, internal conversion coefficients, fluorescence yields, and relative X-ray intensities of the lines.

Atomic-field bremsstrahlung (AFB) is an alternative photon source which can be used to replace the conventional radioactive sources. Palinkas and Schlenk [3] were the first to use this technique for efficiency determination of the solid-state detectors as a function of photon energy who bombarded 10.0 keV electrons on a 10 μgm/cm$^2$ carbon target and observed the bremsstrahlung spectrum at 105°. A few years later, Quarles and Estep [4] and Altman *et al* [5] published their works in which they used the AFB technique to determine the efficiency of a Si(Li) and a HPGe detector in the photon energy range of 2–40 keV and 15–100 keV, respectively.

In this paper, we have demonstrated the usefulness of atomic-field bremsstrahlung as an 'alternative' method for determining the relative efficiency of a Si(Li) detector even at photon energies below 6.0 keV, where not many X-ray lines are available from the conventional radioactive sources. The potential advantages of using the atomic-field bremsstrahlung in efficiency measurement is that the theory is independent of the atomic- and the nuclear-processes which form the theoretical basis for determining the line intensities of X-ray fluorescence sources. In other words, it may be stated that the AFB process can provide an 'independent' photon source with the potential of absolute calibration to the accurate theory.

Pratt and his coworkers [6,7] have calculated the doubly differential cross sections for atomic-field bremsstrahlung process in a wide range of bombarding electron energy and for all atomic numbers. When electrons with kinetic energy $T$ bombard a target of atomic number $Z$, the radiation produced may be a non-characteristic (continuum) with energy $k$ ranging from zero to $T$, the so-called kinematic 'end point' of the bremsstrahlung spectrum. The number of photons of energy $k$, $N_B(k)$ within a photon energy window $\Delta k$, detected by a detector placed at angle $\theta_k$ with respect to the incident beam and subtending a solid angle $\Delta\Omega$ is given by

$$N_B(k) = N_e t\left(\frac{d^2\sigma}{dk d\Omega}\right)\Delta k \Delta\Omega \varepsilon(k), \tag{1}$$

where $N_e$ is the incident electron beam intensity, $t$ is the target thickness, $\varepsilon(k)$ is the photon energy-dependent efficiency of the detector and $\left(\frac{d^2\sigma}{dk d\Omega}\right)$ is the theoretical AFB cross sections.

It is seen from eq. (1) that absolute efficiency measurements would require the precise determination of the target thickness and that of the $N_e$ which is a limiting factor in doing so. However, the relative efficiency $\varepsilon(k)$ can be determined readily from the ratio $N_B(k) / (d^2\sigma / dk d\Omega)$ with much more accuracy since it does not depend on $t$ and $N_e$.

If good relative measurements are available over a desired range of photon energies, the relative efficiency can be placed on an absolute scale by the measurement of one line from a calibrated radioactive source in the region of interest.

## 2. Experimental procedure

A collimated beam of electrons of 7.0 keV and 7.5 keV energies was obtained from our indigenously built electron gun and was incident on semi-thick targets (150 μgm/cm$^2$–600 μgm/cm²) of Ag, Au and Hf which were placed at 45° to the beam. The uncertainty in target thickness quoted by the manufacturer is 20%. The bremsstrahlung spectrum was observed at 90° to the incident electron beam by a Si(Li) detector (active area of 80 mm² and thickness of 5 mm; FWHM = 250 eV at 5.9 keV). The photons emitted from the target reached the detector through a 6 μm thick hostaphan chamber window and an air column of 1.6 cm. The thickness of detector's Be-window was 0.25 mil. The data was collected using a PC-based MCA in about 2500 secs with an average beam current of about 3 nA to avoid any pile-up events. The counting statistics on data points varied between 3–10%. A typical bremsstrahlung energy sepectrum produced from 7.0 keV $e^-$-Ag collisions is shown in Figure 1. The background photons produced from scattered electrons hitting the chamber-wall and hostaphan window were minimised by preventing them from reaching the detector

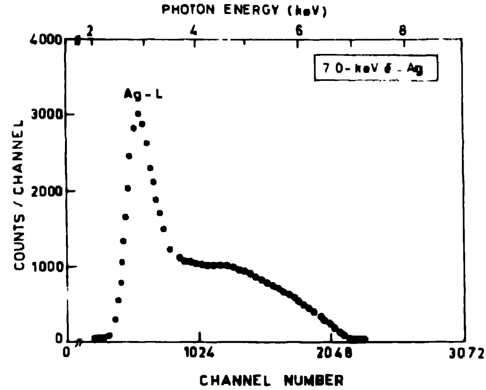


**Figure 1.** Electron bremsstrahlung photon energy spectrum for 7.0 keV electrons incident on a semi-thick (157 μgm/cm²) silver target. Photons were detected at 90° to the incident electron beam direction by a Si(Li) detector

by using a suitable aperture on the Be-window. A more detailed discussions on the experimental arrangements, data acquisition, background subtraction and analysis *etc.* can be found in Refs. [8,9].

## 3. Determination of the efficiency of Si (Li)

Absolute efficiency of the Si(Li) detector was determined from the data of bremsstrahlung spectra in two ways :

(i) by obtaining the 'relative' efficiency of the Si(Li) and making it on an absolute scale,

(ii) by making use of the measured values of all parameters treated with necessary corrections and putting them in eq. (1).

In the 'first' method, the number of photons, $N_B(k)$ obtained from the recorded bremsstrahlung energy spectra with Ag, Au and Hf targets normalised to their respective theoretical bremsstrahlung doubly differential cross sections $\left(\frac{d^2\sigma}{dkd\Omega}\right)$ as obtained from Ref. [7] in a chosen photon energy window $\Delta k$ ($\Delta k$ = 250 eV). The normalised data thus obtained yield the relative efficiency of the detector as a function of photon energy. This is so because the ratio involves only the efficiency parameter which depends on photon energy $k$; the other parameters are independent of $k$ [see, eq. (1)]. The relative efficiency is then put on an absolute scale in an independent way by further normalization to a standard calibrated radio-active $^{55}$Fe-source at a photon energy of 5.9 keV. For this, the radioactive source is placed at the target position and the emitted Mn-K$_\alpha$ line is recorded. The formula for determining the absolute efficiency of a detector as a function of photon energy $k$, using the characteristic Mn-K$_\alpha$ line is given by [10],

$$\varepsilon(k) = \frac{\text{net area of Mn - K}_\alpha \text{ line}}{\mu C_i(t) \times \text{live time} \times \text{yield} \times 3.7 \times 10^4}, \tag{2}$$

where, net area is the area under the Mn-K$_\alpha$ line appearing at energy $k$, which is directly related to the intensity of the line; $\mu C_i(t)$ is the activity of the isotope at time $t$ in micro-Curies, live time is actual analogue to-digital converter (ADC) non-busy time of data collection in seconds and yield is the branching ratio fraction of the Mn-K$_\alpha$ line by the source. The factor 3.7 × 10$^4$ converts radioactive disintegrations per second to micro-Curies, since 1 Curie = 3.7 × 10$^{10}$ disintegrations per second. The $\mu C_i(t)$ is calculated by the following relation

$$\mu C_i(t) = \mu C_i(t_0) \exp\left[\frac{-0.693.\text{decay.time}}{\text{half.life}}\right], \tag{3}$$

where, $\mu C_i(t_0)$ is the activity of the isotope at the initial time $t_0$ in microCuries. Practically, the absolute efficiency or the total detection efficiency of the detector is broken into two factors *i.e.* into the 'geometrical' efficiency $(\Delta\Omega/4\pi)$ and the 'intrinsic' efficiency. The latter one depends on transmission through the detector's Be-Window, Au-contact and Si-dead layer. $\Delta\Omega$ is simply the solid angle element that the front surface of the detector subtends at the source of photon. $\Delta\Omega/4\pi$ in the present configuration is found to be 1.93 × 10$^{-4}$ Sr. By determining the value of $\mu C_i(t)$ from eq. (3) and substituting its value into eq. (2), the $\varepsilon(k)$ is calculated. At $k$ = 5.9 keV, the value of $\varepsilon(k)$ is found to be 1.71 × 10$^{-4}$.

In the 'second' method, the calculations for detector's absolute efficiency $\varepsilon(k)$ are made by using the values of measured parameters after treating them with proper corrections [see, eq. (1)] and theoretical bremsstrahlung doubly differential cross sections [7]. Since, we have done experiments with targets which are thick enough to arrest the impinging electrons but thin enough to transmit a substantial number of photons, it was necessary to do corrections in the experimental data, namely, in $N_B(k)$ and in $N_e$ for the solid-state-effects *i.e.* for electron energy loss, photon attenuation and electron backscattering events. The details of various corrections are given elsewhere [11].

As a result, the absolute efficiency of the Si(Li) detector at a photon energy $k$ is obtained using eq. (1) as

$$\varepsilon(k) = \frac{N'_B(k)}{N'_e \left[\frac{d^2\sigma}{dk d\Omega}\right]_{\text{Theory}} N_t \Delta k \Delta\Omega}, \tag{4}$$

where, $N'_B(k)$ = number of bremsstrahlung photons after corrections for electron energy loss and photon attenuation in a photon energy window $\Delta k$, $N'_e$ = number of incident electrons on the target after correction for electron backscattering events and $N_t$ = target thickness (number of atoms/cm$^2$).

Using eq. (4), we have determined the absolute efficiency of the Si(Li) detector in the photon energy range of 2.0 keV to 7.5 keV from the data of 7.0 keV and 7.5 keV $e^-$-Au, Ag and Hf collisions. The calculated values of $\varepsilon(k)$ from this method are found to agree

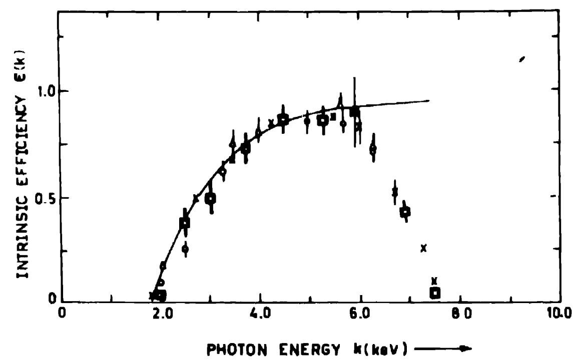


**Figure 2.** Intrinsic-efficiency of a Si(Li) detector *versus* photon energy for (i) 7.5 keV electrons on Au 200 μgm/cm$^2$ (×) and Hf. 600 μgm/cm$^2$ (□) using 'first' method; (ii) 7.0 keV electrons on Ag 157 μgm/cm$^2$ (Δ) and Au. 200 μgm/cm$^2$ (O) using 'second' method (•) · datum corresponding to the radioactive $^{55}$Fe-source Error bars on data points are purely statistical in nature while the error bar on the source point corresponds to the uncertainty in target thickness The solid line curve is the simple photo-absorption model for the efficiency The drop-off at about 6.0 keV is an electron energy-loss effect in bremsstrahlung spectra of the semi-thick targets studied in the present impact energy range

with those obtained from the 'first' method within the uncertainty of the target thickness of about 20% and they are shown in Figure 2 by respective symbols for comparison.

## 4. Results and discussion

The absolute efficiency $\varepsilon(k)$ of a Si(Li) detector as a function of photon energy in the range of 2.0 keV–7.5 keV is shown in Figure 2. The $\varepsilon(k)$ determined from data of each target at arbitrarily chosen photon energy $k$, using the 'first' method (see, Section 3) is found to agree with the normalization to the radioactive source within the uncertainty in the target thickness which is about 20%. Furthermore, the calculated values using the 'second' method for detector's absolute efficiency as a function of photon energy are also included in the figure for comparison. Further shown is the scaled theoretical efficiency curve based on a simple photo absorption model using the photo-absorption cross sections of Storm and Israel [12]. We have made the Chi-squares fit to the data to determine the photon energy dependence of the photo-absorption cross section. The curve is given by,

$$\varepsilon(k) = (1 - 0.69k^{-2.76}) \exp\left[-3.11t_a k^{-2.79} - 1.86t_{Be} k^{-2.9}\right.$$
$$\left. - 0.50t_h k^{3.35} - 37.96t_{Au} k^{2.52}\right], \qquad (5)$$

where, $t_a$, $t_{Be}$, $t_h$ and $t_{Au}$ are the air gap, Be, hostaphan and gold layer thicknesses in mg/cm$^2$ respectively. In the above fit, the values of $t_a$, $t_{Be}$, $t_h$ and $t_{Au}$ were taken to be 1.6 cm, 25 μm, 6 μm and 200 Å, respectively. No attempt was made to fit the M-Shell edge effect in the efficiency model The fitted efficiency curve as shown in Figure 2 by a solid line, shows a good agreement with the experiment ($X^2$ = 1.21 per degree of freedom). The factor preceeding the exponential, corrects for silicon escape.

A few interesting features can be noted from the data for targets studied in the present work. First, the data deviate from the curve from ~6.0 keV upwards. This is due to energy-loss experienced by the electron beam which suffers multiple collisions in the semi-thick targets. This slow drop off is a characteristics of the 'thick target' effect. However, the $\varepsilon(k)$ behaviour with photon energy for thin targets would show, in contrast, a sharp drop off at the 'end point' or at the maximum possible photon energy. This is a characteristics of the 'thin-target' bremsstrahlung end points. Further, a silicon K-X-ray at about 1.7 keV may be induced due to a monolayer of silicon on the targets due to contamination by pump oil. This peak can be avoided by a careful attention to a good vacuum (*i.e.* better than $1 \times 10^{-6}$ torr). Second, the absolute efficiency curve calculated from the photoabsorption data of Storm and Israel [12] shows a good agreement with the measured efficiency below 6.0 keV for each target with the normalisation to the radioactive source within the uncertainty in the target thickness of about 20%.

## 5. Conclusions

In this paper, we have demonstrated the use of atomic-field bremsstrahlung for determining the relative efficiency of a Si(Li) detector below 6.0 keV by measuring the bremsstrahlung photon energy spectra from Ag, Au and Hf semi-thick targets bombarded with electrons of 7.0 keV and 7.5 keV energies. The relative efficiency is placed on an absolute scale by normalisation to a calibrated radioactive source or to the absolute theoretical bremsstrahlung cross sections, provided an accurate knowledge of thickness of the target is known. With some care, the background can be minimised. We believe this technique to be as precise as the conventional technique using calibrated radioactive sources and to be useful for determining $\varepsilon(k)$ for the entire efficiency curve in one run with a good statistics.

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